CHAPTER 5
REPAIR TYPES AND COSTS

5.1 OVERVIEW

The analysis of repair types and associated costs is required for several reasons. First, the estimation of criteria pollutant emission reductions is through knowledge of the different malperformances and their individual or synergistic effects on emissions. The methodology to connect malperformance to emission increases was first developed by Radian (1988) and subsequently updated by EEA in 1990. The types and rates of malperformances found in this repair study serve as validation for the malperformance model of emission benefits. Second, the average cost of repair has a significant bearing on program costs and cost-effectiveness. Hence, costs derived in this section are utilized in the following sections of this TSD to derive program cost-effectiveness. Third, repair costs have specific implications for the citation penalty structure. Since ARB plans to continue with the existing citation penalty structure, the repair costs are contrasted to the penalties to estimate their deterrence potential.

The analysis is described in three parts. First, the types of repair and their frequency of occurrence is analyzed. Second, the benefits of repair in terms of reduced peak smoke as measured on the snap-acceleration mode is derived from the data. Third, the cost of the various repairs and the implications for the citation penalty structure are discussed.

5.2 TYPES OF REPAIR

The data base from the Truck Repair Study included written comments by mechanics on the types of repair. These comments were the basis for dividing the repairs performed into a few specific categories. Unfortunately, mechanics' written comments on repairs were unclear in

some cases so that the exact sequence of repair, and costs and benefits for less-than-complete repair could not be fully determined. As a result, this analysis focuses on the endpoint of all repairs.

The repair sample is based on data from all 71 trucks recruited, even though three were not fully repaired for reasons previously discussed. Details of the types of trucks included in the repair sample is shown in Table 5-1. The sample has good representation of the heavy-heavy duty diesels makes. The sample of vehicles in the medium duty category was small and a separate analysis would provide results of little significance. In addition, the types of repair for these engines are quite similar to those for heavy-heavy duty engines. No light-heavy duty diesels were included in the sample, since they are not normally found at weigh stations where the vehicles were recruited for this study.

High smoke emissions are normally due to:

- **Improper transient air fuel ratio control**
- **Problems with the fuel injection system or fuel injection timing**
- **Inadequate intake air**

Of these, transient air-fuel ratio control maladjustment is largely responsible for high smoke during the snap acceleration test. Each engine make has different designs that influence fuel injection system characteristics and adjustments to control transient air-fuel ratio. Cummins engines feature fuel injectors with a separate metering pump. Transient air-fuel ratio control is accomplished by modulating the metering pump line pressure under no boost condition, referred to by mechanics as a "no-air pressure" adjustment. Control under turbocharger boost is accomplished by a plunger and bellows (or aneroid) mechanism. Most 1990 Caterpillar and Navistar engines feature a separate injection pump which provides both fuel metering and injection pressure. A separate mechanism, within the injection pump, also with a bellows, accomplishes transient air fuel ratio control (AFRC). Older two-stroke DDC engines and Mack engines are equipped with a throttle

delay, or puff limiter, which essentially prevents high speed transient movements of the fuel rack in response to throttle movements. DDC engines have always featured unit injectors, which include the metering mechanism and the high pressure injection mechanism in a single unit. Unit injectors with electronic control of metering and injection timing are utilized in 1991 and later engines from several manufacturers. All of the transient air fuel ratio controls are applicable only to turbocharged diesel engines, but all engines in the sample are turbocharged. As shown in Table 5-2, 70 percent of engines (50) in the repaired sample had defects in this part of the system. In addition, this rate was very similar across different manufacturers' engines, and very similar to the rate observed in the repair sample utilized in the 1990 TSD.

A large percentage of the other repairs were also associated with the rest of the fuel control system. These included adjusting the governor, fuel rack position or injection timing, which are necessary adjustments on all diesel engines. The impact of governor tampering on smoke opacity is engine model dependent, but governor tampering is relatively common on Cummins engines. The metering pump was rebuilt or replaced for a large fraction of the sample. Finally, injectors (or injection nozzles) were repaired or replaced in over one third of the engines (20) in the sample.

Most of the 1991 and later engines featured electronic control of injection timing as did a few 1988-1990 engines. In particular, the DDC Series 60 engines in the sample were all electronically controlled, and <u>every Series 60 Engine</u> in the sample was given an electronic control module program update. It was not clear if this was necessary in all cases; in at least one case, there was no observed change in smoke opacity. All electronically controlled engines had their internal diagnostics queried, but no system faults were found. This may be because current diagnostic systems in heavy-duty diesel engines are not designed to recognize faults causing high smoke on the snap-acceleration test. There are also some concerns on the ability of this test to recognize malperformances in electronic systems. The

replacement of the air filter was another common repair performed in one-third of the sample. Turbochargers needed replacement on 4 of 71 turbocharged engines but one was due to leaky oil seals, and was not repaired in this study.

TABLE 5-1
REPAIR SAMPLE COMPOSITION
BY ENGINE MODEL

Manufacturer	Pre-1980		1980-1987		1987-1990		1991+	
	No.	Model	No.	Model	No.	Model	No.	Model
Cummins	7	NTC	13 3	NTC L-10	6 3	NTC L-10	1	L-10
Caterpillar	1 1	1693TA 3306B	7 2	3406 3306	2 1 1	3406 3306 3176	1 1	3176 NTC365
DDC	1 2 1	8V71 6V92 8V92	1 2	8V71 6L71	2	Series 60	3	Series 60
Navistar	1	DT466	1	DT466	--	--	--	--
Mack	1	E6-315	1	EM6-350	3	EC6-350	--	--
Other	--	---	--	--	--	--	2	4BD2C (Isuzu)

TOTALS	**15**	**---**	**30**	**---**	**18**	**---**	**8**	**---**

TABLE 5-2
DISTRIBUTION OF REPAIR TYPES
IN SAMPLE

	Pre-1980		1980-1987		1987-1990		1991+		Rate*
Sample Size	15		29		18		8		70
	A*	R*	A*	R*	A*	R*	A*	R*	%
Air Filter	--	2	--	4	--	--	--	2	12.9
Turbocharger	--	2	--	--	--	1	--	(1)*	4.3
Intake	--	--	--	2	--	1	--	__	2.6 (manifold)
									1.4 (Intercooler)
AFRC	5	6	20	7	4	7	1	0	71.4
Injection Pump	2	2	3	10	3	5	1	0	37.1
Overhead	3	2	4	2	9	0	1	0	30.0
Injectors	2	3	2	8	2	8	0	1	37.1
Injection Timing	1	0	1	0	(1)	0	1	0	5.7
Governor	0	0	3	1	0	1	0	0	7.1
Valves	3	0	0	0	2	0	0	0	7.1
Exhaust	0	1	0	0	0	3	0	0	5.7
Electronics	--	--	--	--	2	0	5	0	NA

Numbers in parenthesis are diagnosed but unrepaired defects

*** A is Adjusted, R is repaired or replaced. Rate is calculated as a percent of total sample across all model years.**

In addition, valves were adjusted on several engines, which is part of general tune-up but has limited impact on smoke opacity. The frequency of various types of repairs are summarized in Table 5-2 and the similarity in the repair rates to the observed rates in 1990 is noteworthy. As noted, four vehicles were rejected from the program, three because of the extreme wear that would require an engine rebuild to restore to manufacturer specifications, and one because of extensive tampering resulting in dealer unwillingness to repair the engine. Four additional vehicles were rejected from the program. All four were pre-1991 vehicles, and the dealership based J1667 smoke opacity measurements showed that their opacity was well below the 40 percent criteria established for acceptance. In two of these cases, there were no "field" tests. Two other vehicles (both buses) powered by DDC 8V-71 engines were field tested at relatively high opacities (over 50 percent) but tests at the dealership indicated smoke opacity below 30 percent.

5.3 SMOKE REDUCTION FROM REPAIRS

On average, all four engine year groups showed significant reductions in smoke from repair. The pre-repair and post-repair average values are as follows, excluding the three vehicles where engines were not fully repaired.

	Average Pre-Repair Opacity	Average Post-Repair Opacity
Pre-1980	65.9	22.4
1980-1987	63.6	20.7
1988-1990	56.0	17.3
1991 +	35.0	21.2

As noted previously, post-repair opacity levels were independent of pre-repair levels, so that larger reductions in opacity were obtained from high emitters. A regression analysis of

opacity reduction for pre-1991 vehicles, defined as (pre-repair - post-repair opacity), indicated the relationship between ∆ opacity to pre-repair opacity was given by:

$$\Delta \text{ OP} = -24.34 + \underset{(0.061)}{1.038} \text{ (Pre-Repair Opacity)} \qquad (r^2 = 0.827)$$

where the number is in parenthesis is the standard error of the coefficient. The regression indicated that post-repair opacity was constant as the co-efficient of the relationship between ∆opacity and pre-repair opacity is almost exactly <u>one</u>, confirming that, post-repair opacity levels were independent of pre-repair levels.

The reduction in opacity obtained for 1991 + vehicles were similar to those for pre-1991 vehicles, except in two instances where no meaningful reductions were obtained. Because of the small total sample size, no detailed analysis or regression could be performed. The opacity was generally reduced to the 11 to 20 percent opacity range after repair in six vehicles that exclude the two with minimal post-repair smoke reduction. Hence, the expectation is that a larger sample and better repairs could indicate an average post-repair smoke opacity level of about 15 percent, independent of pre-repair levels. This expectation is also consistent with the fact the certification peak smoke levels for 1991+ engines have declined 50 to 70 percent from pre-1991 certification levels.

5.4 COSTS OF REPAIRS

The Truck Repair Program had operational cost ceilings for repair in order to meet budgetary constraints, and the ceiling was set informally at about $750 (this is more than the standard authorized amount, and was intended as an internal budgetary guideline). This amount was supplemented by manufacturers for an additional $250 to $500, as required. In a few instances where the bill was over $1300, the customer agreed to pay the amount not covered by ARB or the engine manufacturer. Other than the three engines for which repairs were incomplete, all other engines were repaired to levels determined to be adequate by the dealers <u>without regard to cost.</u>

Most repairs include a base cost associated with diagnostics and dynamometer testing so that these costs alone, independent of repairs, added a total of $120 to $180 representing 1

to 2 hours of mechanics time (typically @ $60/hr) and a dyno fee of $60 to $70.

The data from the repair invoices submitted to the ARB allowed determination of actual costs of repair. Mechanics did not in all cases provide a breakdown of both part price and labor costs for each component repaired. In order to disaggregate costs of each of the types of repair specified in Table 5-2, data from all 68 repaired vehicles in the sample were utilized to derive data on the cost of repair by component. Each engine had one to six different types of repair among the 12 possible repair categories. Technology differences were recognized for transient air-fuel ratio controls, and costs were different in this category by manufacturer. In other categories of repair, costs were assumed to be relatively independent of manufacturer and model type, and most costs could be determined with a range of $\pm$10 dollars or $\pm$10 percent variability, whichever was larger. Variations within this range reflected different mechanics' costs as well as labor hour differences that may have been caused by engine configuration and vehicle specific installation details. The determination of individual category specific repair costs was preceded by an adjustment to the total cost for the cost of diagnostics and a "dyno test" to obtain a total repair cost. Costs were then allocated to various categories of repair and the results are shown in Table 5-3.

Since the dealers were aware of the repair cost "expectation" of $500, there may have been some incentive to pad the bills with unnecessary labor. It is difficult to confirm if this happened, but there are six or seven repair bills where the costs are well above expectations based on the repair cost list compiled in Table 5-3, plus diagnostic costs. Some bills may reflect genuine difficulties in diagnostics, or may reflect an engine configuration that is hard to access, so that no attempt was made to second guess the mechanic. In nine cases, however, the first set of repairs proved unsatisfactory, and these engines were subjected to a second set of repairs. In four of nine cases, the second set of repairs were performed free by

TABLE 5-3
TYPICAL REPAIR COSTS

	Cost Range ($)
Transient Air-Fuel Ratio Control	
- Adjust No Air Pressure (Cummins)	120-150
- Replace AFC Plunger/Bellows (Cummins)	300-350
- Adjust AFRC (Caterpillar/Navistar)	200-250
- Replace Throttle Delay (DDC)	275-335
- Replace Puff Limiter (Mack)	100-120
Adjust Governor	100-150
Adjust Fuel Rack	100-130
Adjust Injection Timing	160-220
Fuel Pump - Repair	325-400
Replace	875-950
Replace Unit Injectors (each)*	300-350
Replace Injection Nozzles (6)	300-400
Replace Air Filter	85-135
Replace Turbocharger	700-800
Replace Intercooler	650-750
Reset Valve Timing	90-100
Replace Exhaust Manifold	300-400
Electronic Control Unit Update	120-150
Rebuild Engine*	5000 and Up

*** Obtained from direct dealer quotes, as such repairs did not occur in the study.**

the same dealership or by another sister dealership under the repair warranty. Average charges for the second set of repairs for the other four trucks was $652; when averaged over the entire truck sample, the average costs are increased by less than $50. In effect, the dollar amount of incremental costs from incorrect repairs or unnecessary billing is estimated to be $50-$100 at most. These excess costs may also occur in real world situations, so that actual repair costs were used in developing cost-effectiveness estimates.

In addition to the above, the costs also include repairs that are only marginally related to the smoke problem. For example, several engines had the valves adjusted, and this can have only very limited impact on smoke. In addition, several engines had all of the injectors replaced even though only one or two may have required replacement. Hence, the stated repair costs for a small group of engines are higher than the minimum required repair costs.

The average costs for the sample of 68 fully repaired engines are as follows:

Pre-1980	**$732**
1980-1987	**$565**
1987-1990	**$827**
1991+	**$433**

Reference to Table 5-2 reveals the reasons why the pre-1980 and 1987-1990 vehicle exhibited higher average costs; in each set, there were some relatively rare repairs that were expensive and which inflated the average cost. For the pre-1980 engines, two engines had their turbochargers replaced. In the 1987-1990 vehicle sample, one engine had an intercooler replaced and another had a new injection pump installed. The replacement parts increased costs by over $750 per engine, but the 1980-1987 sample did not have any similar repairs. A more realistic representation is to average costs across the three model year strata to obtain an average of $652.

Average repair costs for the 8 1991 and newer engines was only $433, and this figure is lower than those for previous years largely because there were no major replacement part

costs. This is due to the fact that the trucks are, on average, less than 5 years old, and the cost estimate may be quite reasonable for vehicles 2 to 6 years old (vehicles less than 2 years old are typically covered by manufacturers new engine warranty). However, as these trucks age, it is likely that average repair costs will increase due to the need to replace worn turbochargers, intercoolers, injection pumps and injectors.

Typically, heavy-heavy duty engines are rebuilt at about 400 to 500 thousand miles of use or every 6 to 8 years, so that the finding that all pre-1991 engine groups had similar average repair costs is not surprising, as the engines are constantly renewed. Medium-heavy duty engines are typically rebuilt at about 250 to 300 thousand miles of use, which corresponds to a similar time interval of 6 to 8 years due to their lower annual use. Hence, repair costs can be modeled as a two-step process, one for the initial six to eight year period and the second during the nine to twenty-five year period.

Costs of an engine rebuild are quite high, starting at $5000 for an "in-frame" rebuild to nearly double that for a factory rebuild. As noted, eight vehicles were not admitted into the program, and four of these had engines which were rebuild candidates. In addition, one of the 71 engines was found to be excessively worn. This engine, along with the four rejected, reflect the fraction of the sample needing a rebuild. However, the rebuild costs are not counted towards the total program costs since an engine that is very worn has limited remaining operational life. A program such as the HDVIP might force an owner to rebuild the engine at a specific time, but this would constitute accelerating an event that was likely to occur in the relatively short term. As a result, costs of engine rebuild and replacement are not explicitly considered in this analysis.